WEATS 2006

FUNDAMENTALS, INTRODUCTION TO WIND ENERGY

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TOPICS

Energy and Power

Wind Characteristics

Wind Power Potential

Operation of Wind Turbines

Power Curves

Estimation of Annual Energy Production

Economics

ENERGY AND POWER

ENERGY, ABILITY TO DO WORK

ENERGY = FORCE * DISTANCE

Electrical Energy , kWh

POWER = ENERGY/TIME

Generator Size, kW

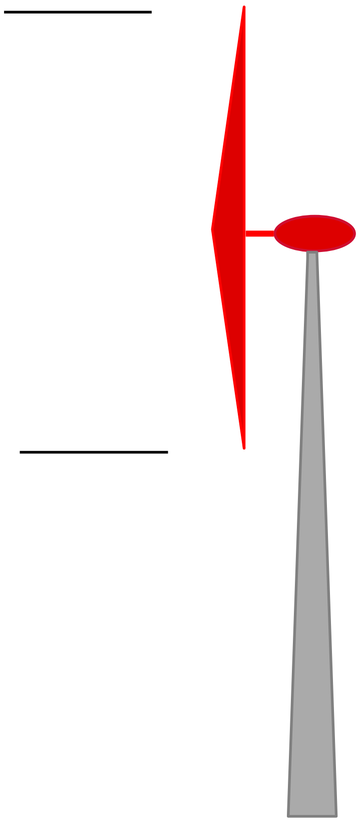
$$P = 0.5\,\rho\,v^3 A$$

P power, Watt

ρ density of air, kg/m^3

v wind speed, m/s

A area, m^2

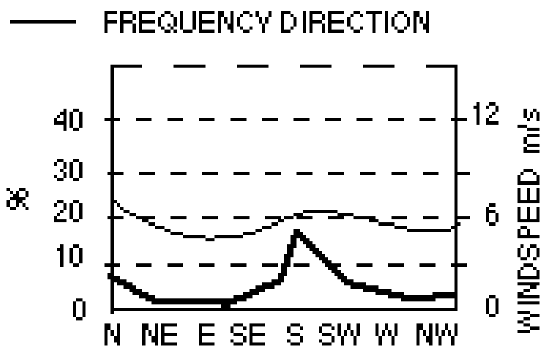


WIND CHARACTERISTICS AND RESOURCE

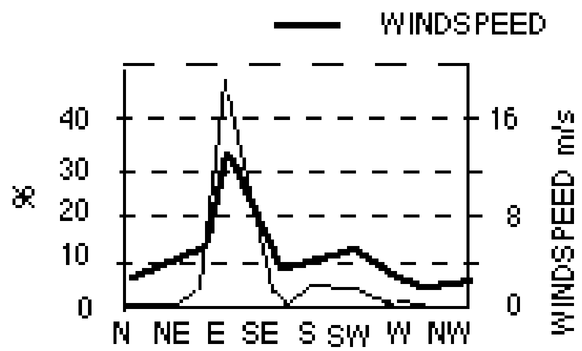
- Wind Speed
- Wind Direction
- Sample Rate, 1 Hz
- Averaging Time, 1 hr
- Histograms (method of bins)
- Wind speed change with height

WIND ROSE

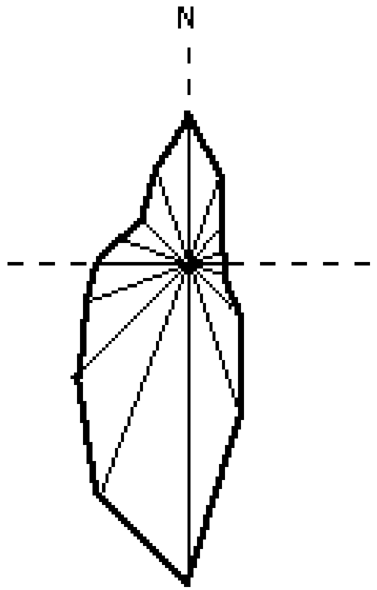
CONTINENTAL TRADE WINDS

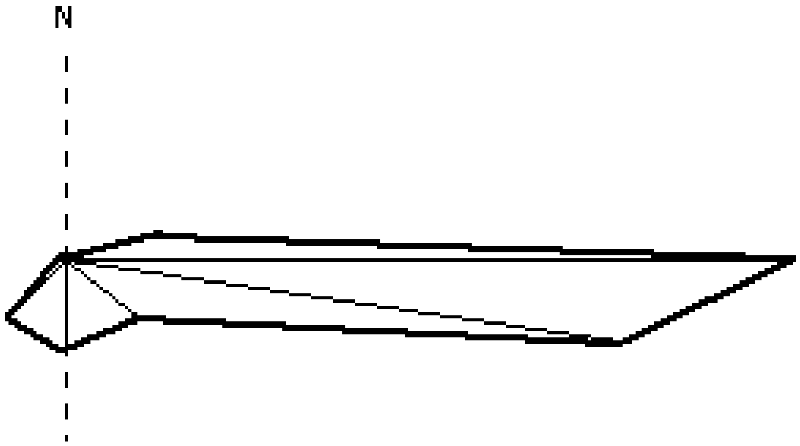


Amarillo, TX



Kahua Ranch, HI





FLAGGED TREE, HAWAII

AVERAGE WINDSPEED, 10 m/s

CALCULATION POWER/AREA WIND SPEED FREQUENCY HISTOGRAM

For time period selected

month, season, year

AVERAGE WIND SPEED = $\Sigma\, F_j * V_j$

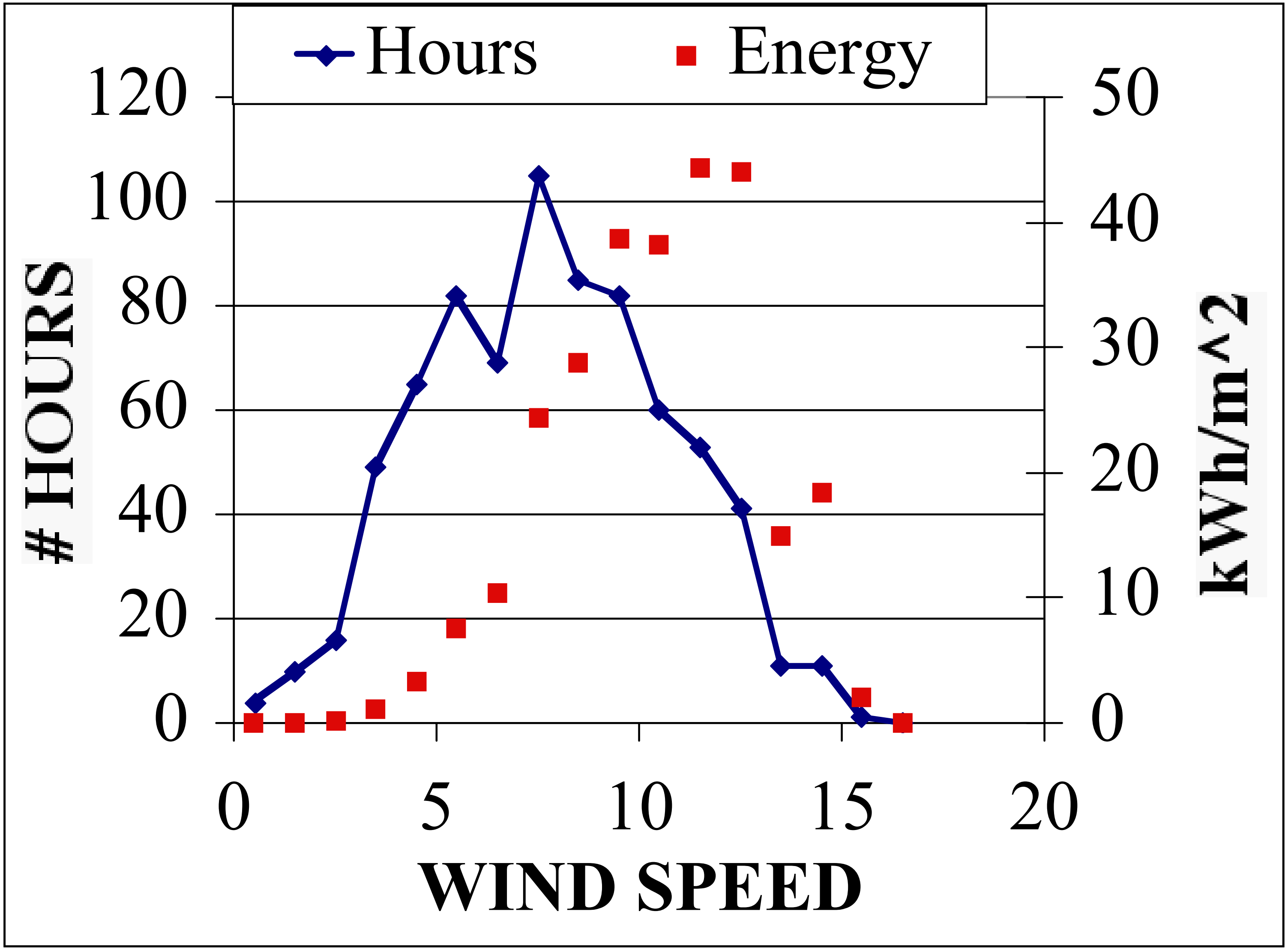
POWER/AREA = $0.5 * \rho * \Sigma\, F_j * V_j^3$

Speed m/s	# hr	Freq	Fj * Vj	Fj * Vj3
0.5	4	0.005	0.00	0.00
1.5	10	0.013	0.02	0.05
2.5	16	0.022	0.05	0.35
3.5	49	0.066	0.23	2.92
4.5	65	0.087	0.39	8.24
5.5	82	0.110	0.61	18.97
6.5	69	0.093	0.60	26.35
7.5	105	0.141	1.06	61.61
8.5	85	0.114	0.97	72.60
9.5	82	0.110	1.05	97.78
10.5	60	0.081	0.85	96.60
11.5	53	0.071	0.82	112.11
12.5	41	0.055	0.69	111.37
13.5	11	0.015	0.20	37.64
14.5	11	0.015	0.21	46.64
15.5	1	0.001	0.02	5.18
16.5	0	0.000	0.00	0.00
SUM	744	1.00	7.8	698

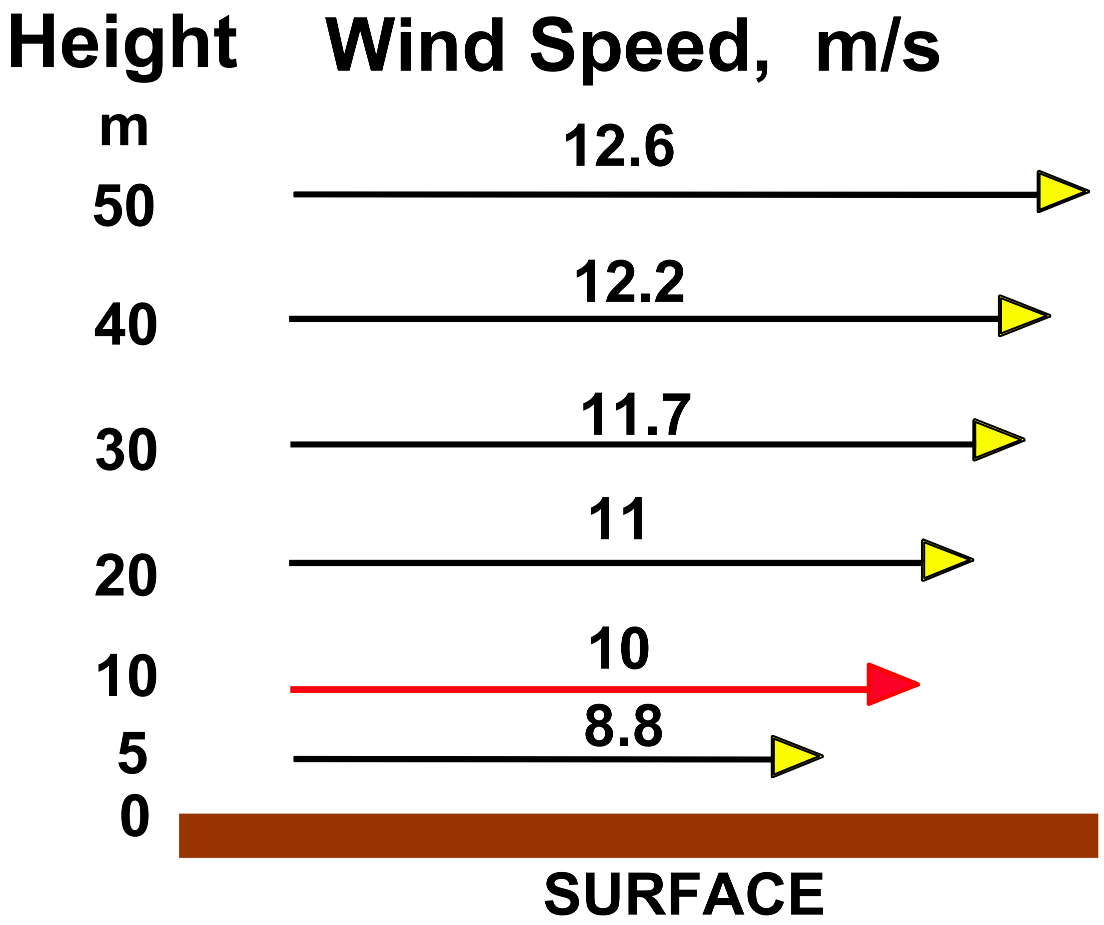
$P/A = 0.5 * 1.1 * 698 = 384 \quad W/m^2$

Perryton, TX Jan 02, 50 m ht

WIND SPEED & ENERGY, Perryton, TX



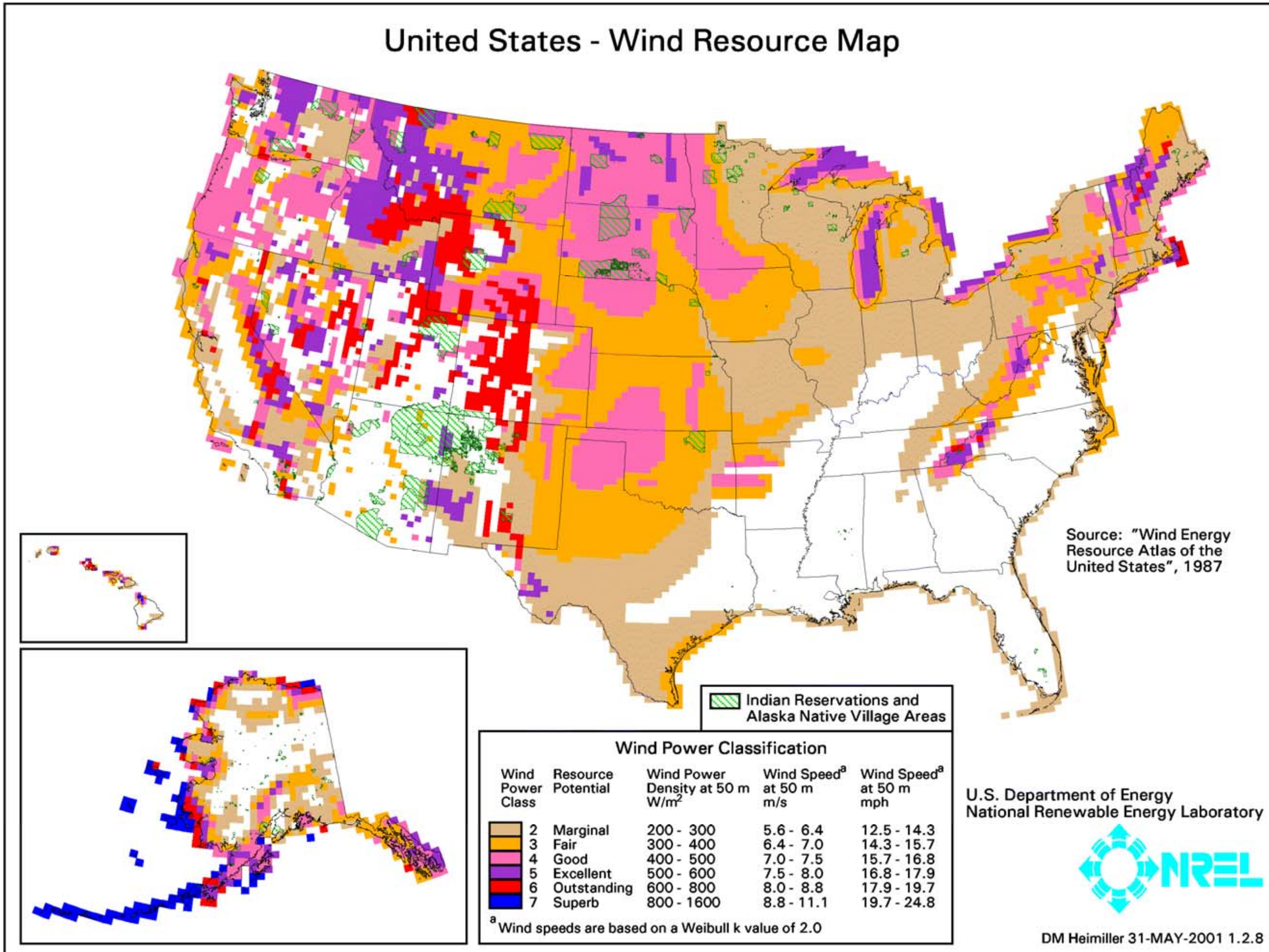
WIND SHEAR


Height
Wind Speed, m/s
m
12.6
50
12.2
40
11.7
30
11
20
10
10
8.8
5
0
SURFACE

WIND POWER POTENTIAL

Wind Speed Histograms are used to determine Wind Class

Wind Class	W/m^2 at 50 m
3	300 - 399
4	400 - 499
5	500 - 599
6	600 - 800
7	> 800


United States - Wind Resource Map
Source: "Wind Energy Resource Atlas of the United States", 1987
Indian Reservations and Alaska Native Village Areas
Wind Power Classification
Wind Power Class | Resource Potential | Wind Power Density at 50 m W/m2 | Wind Speed[a] at 50 m m/s | Wind Speed[a] at 50 m mph
2 Marginal 200 - 300 5.6 - 6.4 12.5 - 14.3
3 Fair 300 - 400 6.4 - 7.0 14.3 - 15.7
4 Good 400 - 500 7.0 - 7.5 15.7 - 16.8
5 Excellent 500 - 600 7.5 - 8.0 16.8 - 17.9
6 Outstanding 600 - 800 8.0 - 8.8 17.9 - 19.7
7 Superb 800 - 1600 8.8 - 11.1 19.7 - 24.8
[a] Wind speeds are based on a Weibull k value of 2.0
U.S. Department of Energy
National Renewable Energy Laboratory
NREL
DM Heimiller 31-MAY-2001 1.2.8

OPERATION OF WIND TURBINES

DRAG AND LIFT

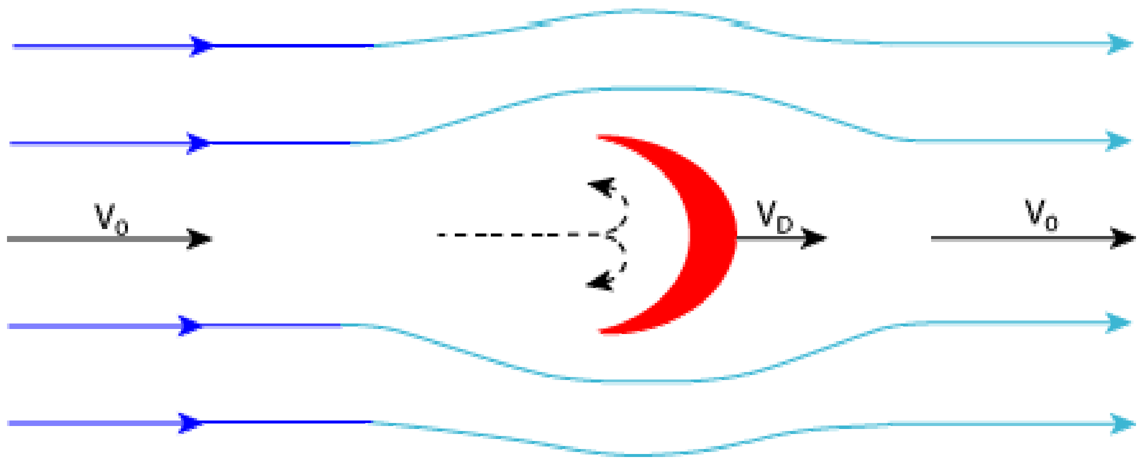
AERODYNAMICS

OPERATION, TORQUE-RPM

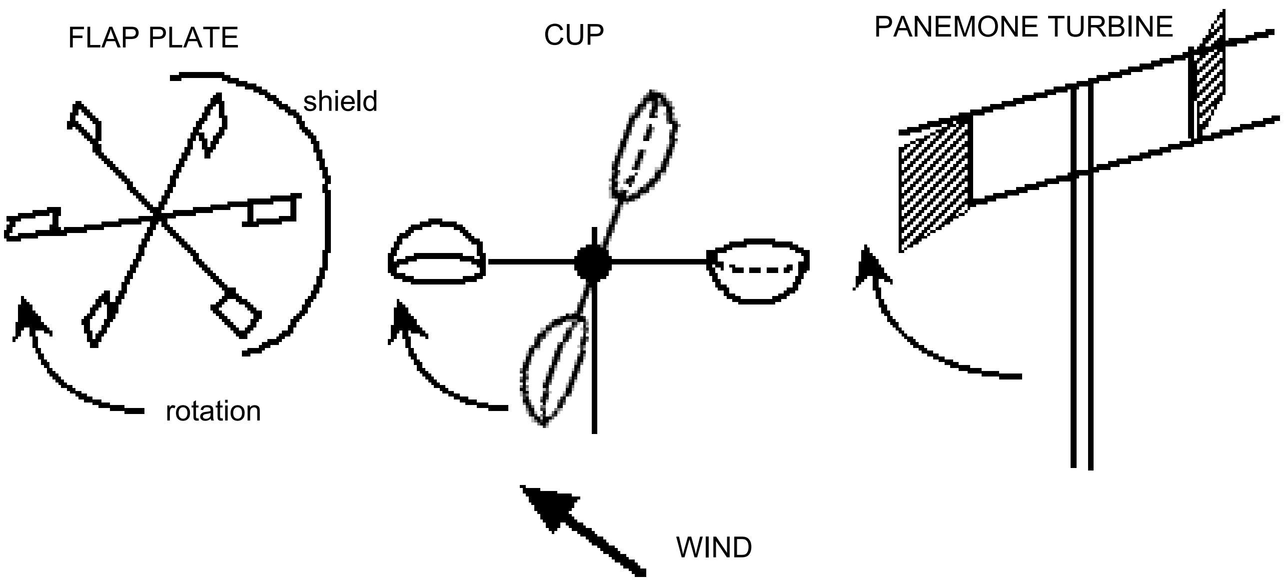
OTHER

POWER CURVES

DRAG



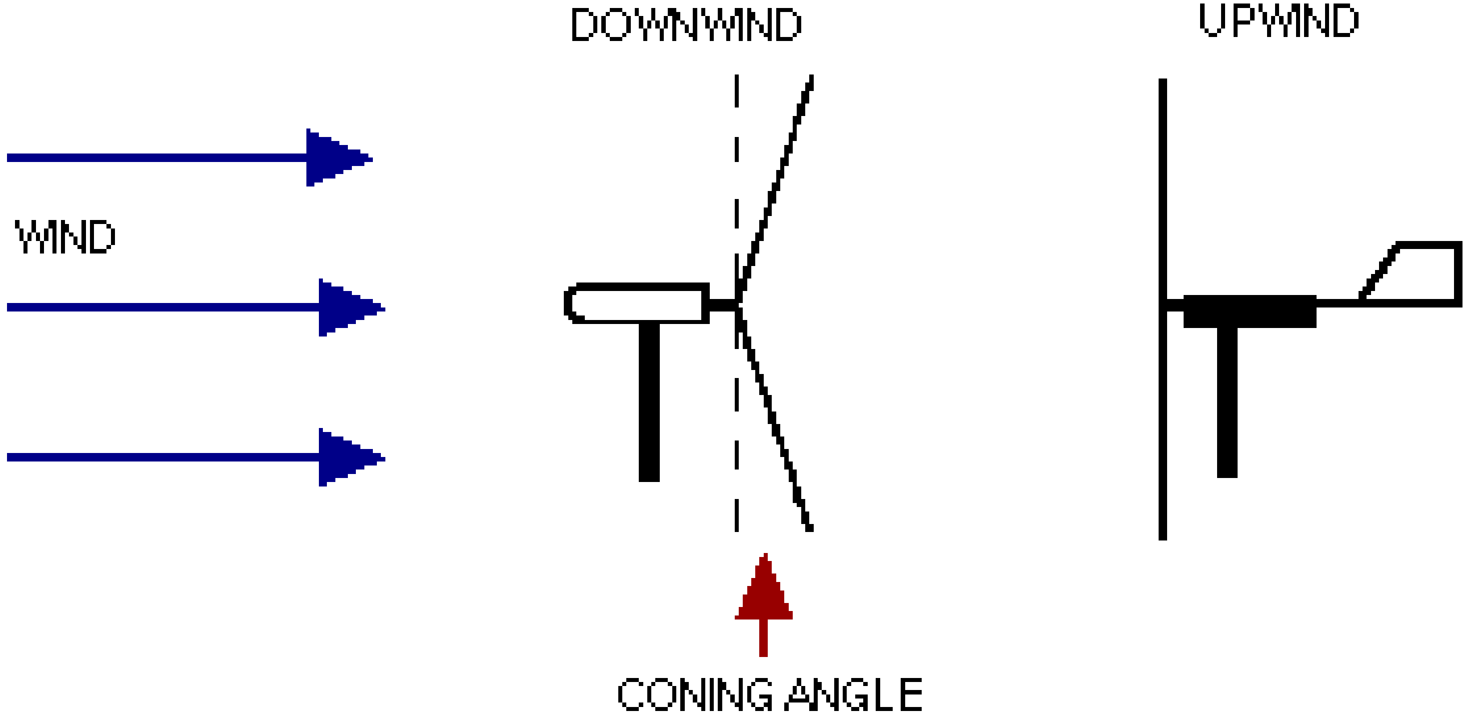
V0
VD
V0



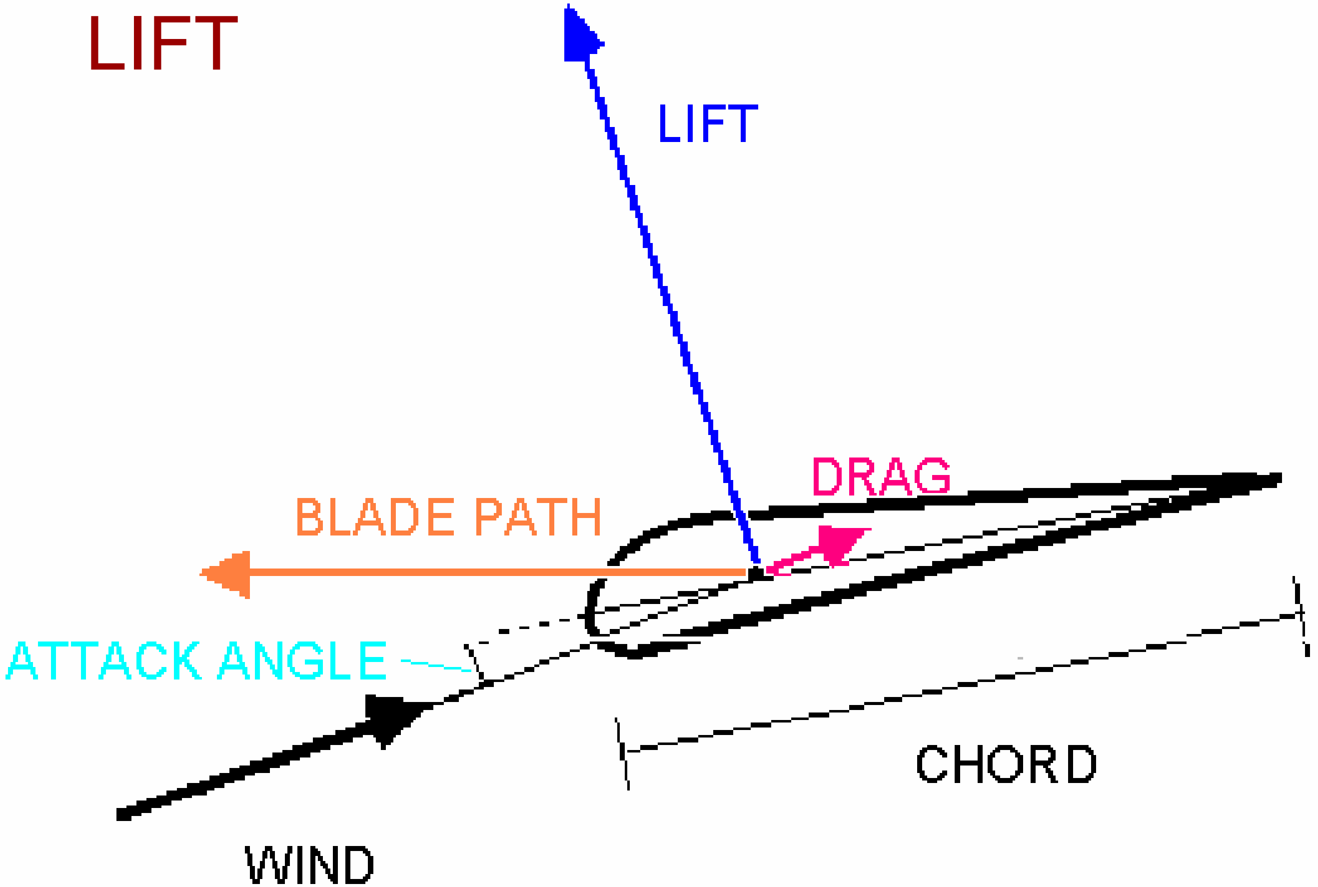
FLAP PLATE
shield
rotation
CUP
PANEMONE TURBINE
WIND

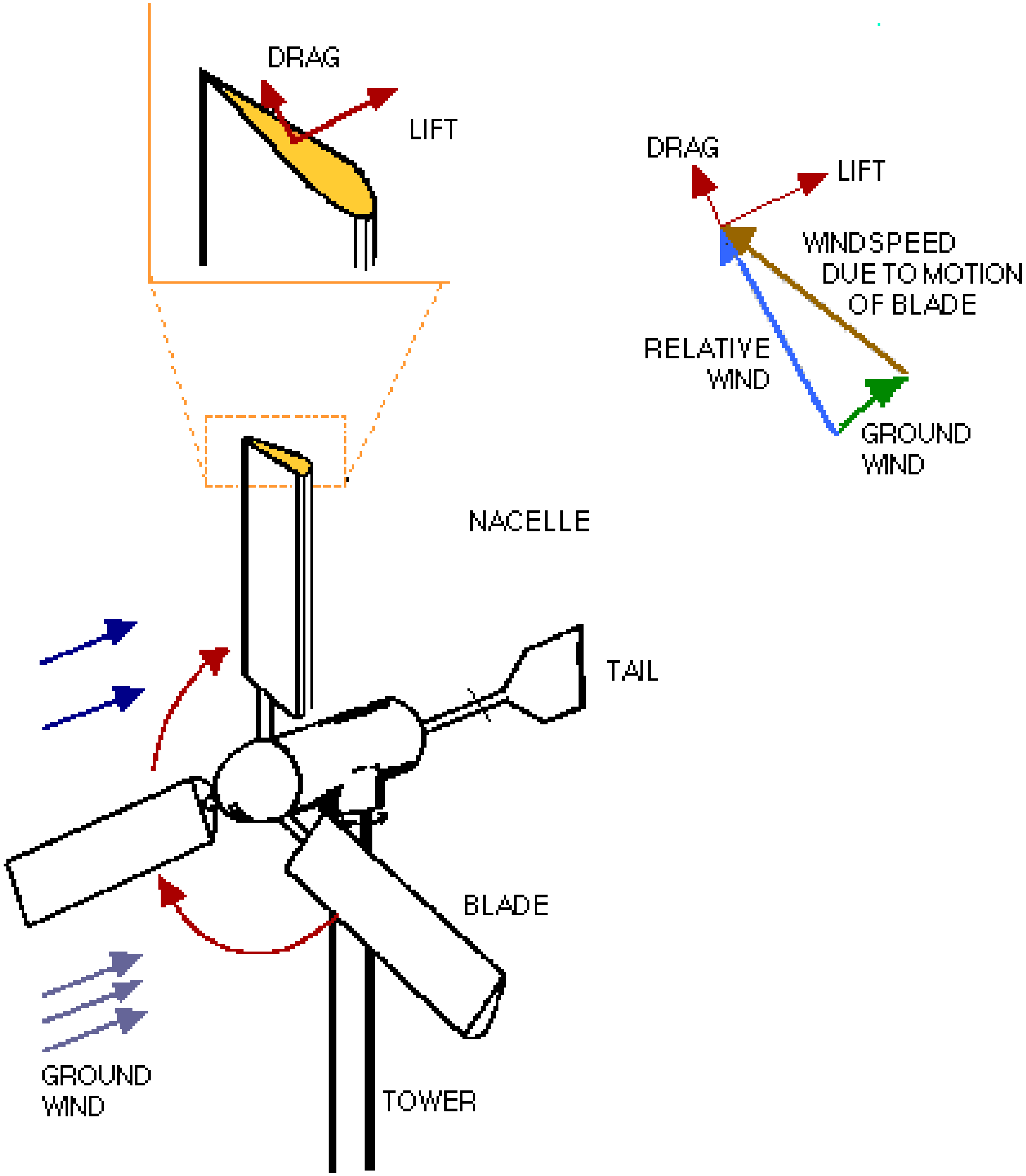
TYPES

HAWT VAWT


DOWNWIND
UPWIND
WIND
CONING ANGLE

LIFT




DRAG
LIFT
DRAG
LIFT
WINDSPEED
DUE TO MOTION
OF BLADE
RELATIVE
WIND
GROUND
WIND
NACELLE
TAIL
BLADE
GROUND
WIND
TOWER

EFFICIENCY

ROTOR

GEAR TRAIN

GENERATOR

POWER COEFFICIENT

C_P = POWER OUT/POWER IN THE WIND

MAXIMUM FOR ROTOR = 59%

For WIND SYSTEM, MEASURED

40 TO 50%

POWER = TORQUE * RPM

- VARIABLE RPM (MAX C_P)
  - Permanent magnet alternator,
  - Enercon ring generator
  - Inverter, variable frequency to constant frequency
- CONSTANT RPM (induction generator)
  - MAX C_P at only one wind speed
- CONSTANT TORQUE (farm windmill)

CONTROL

FIXED PITCH (STALL)

VARIABLE PITCH

YAW (MOTOR, TAIL)

BRAKE

- AERODYNAMIC, MECHANICAL, ELECTRICAL

OTHER

AVAILABILITY

RATED POWER (generator size)

CAPACITY FACTOR (AVERAGE POWER)

CF = (AKWH/8760)/RATED POWER

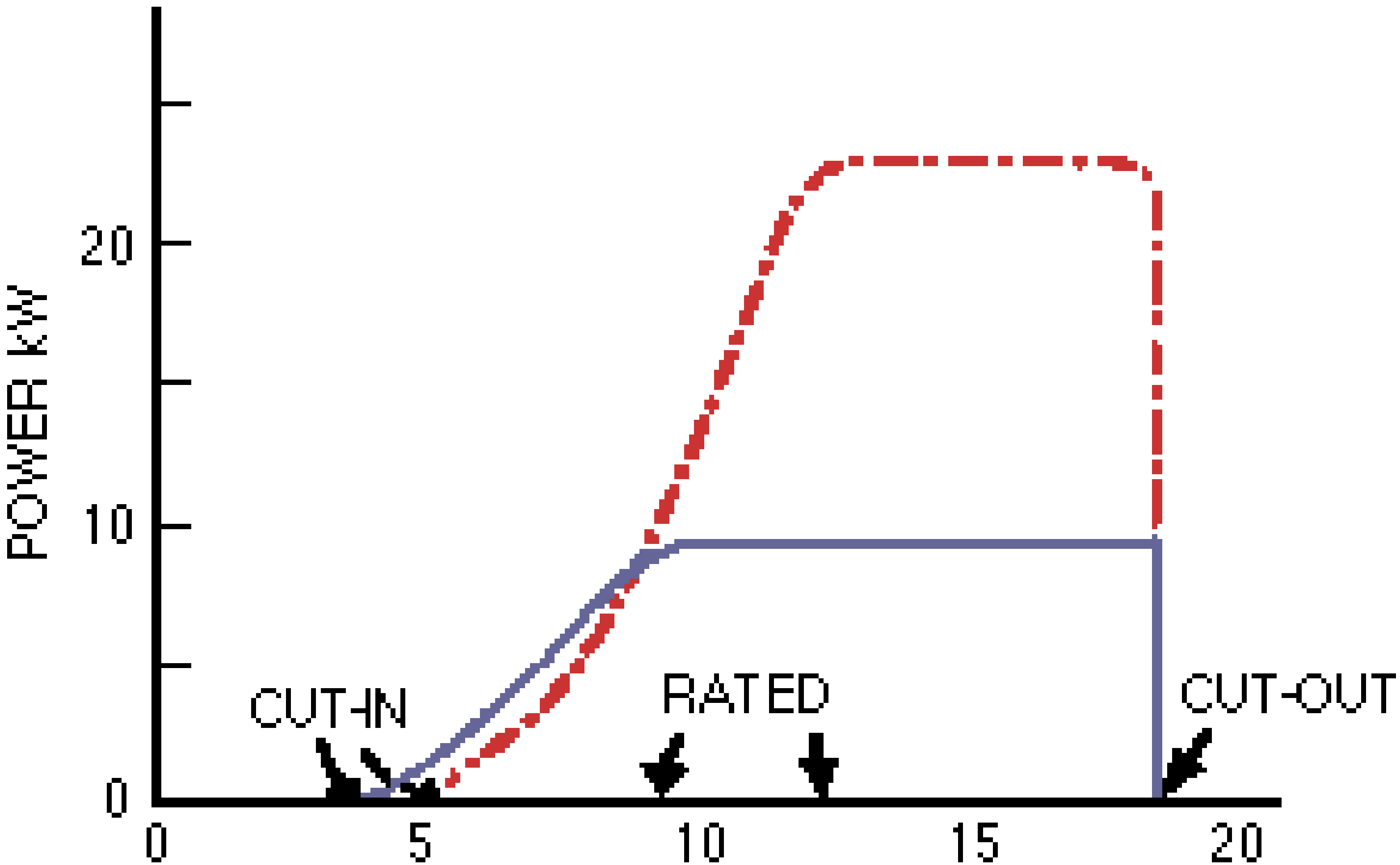
ANNUAL CFs for LARGE WIND TURBINES

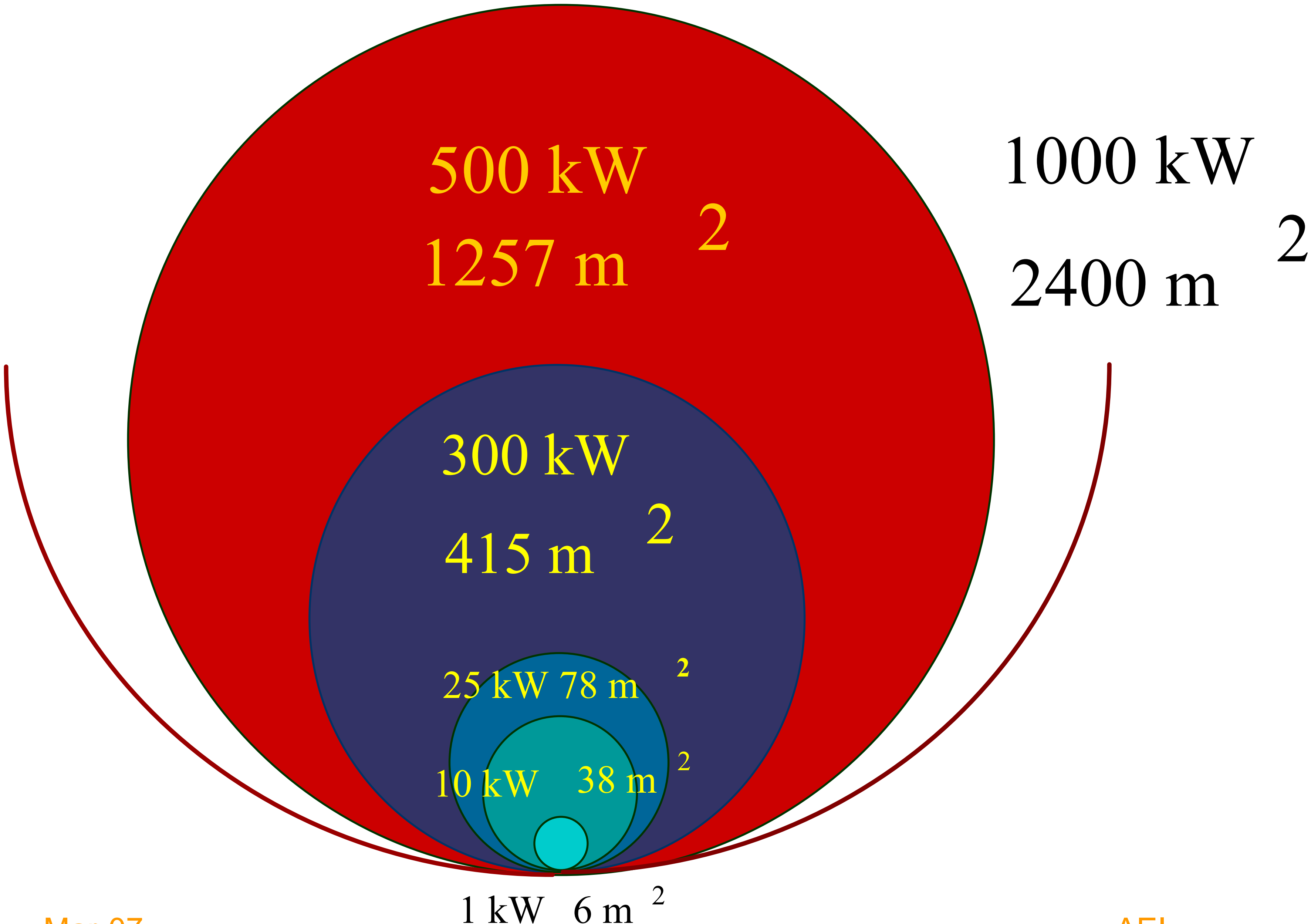
30 to 40%

ONE MONTH, 60% Feb 02

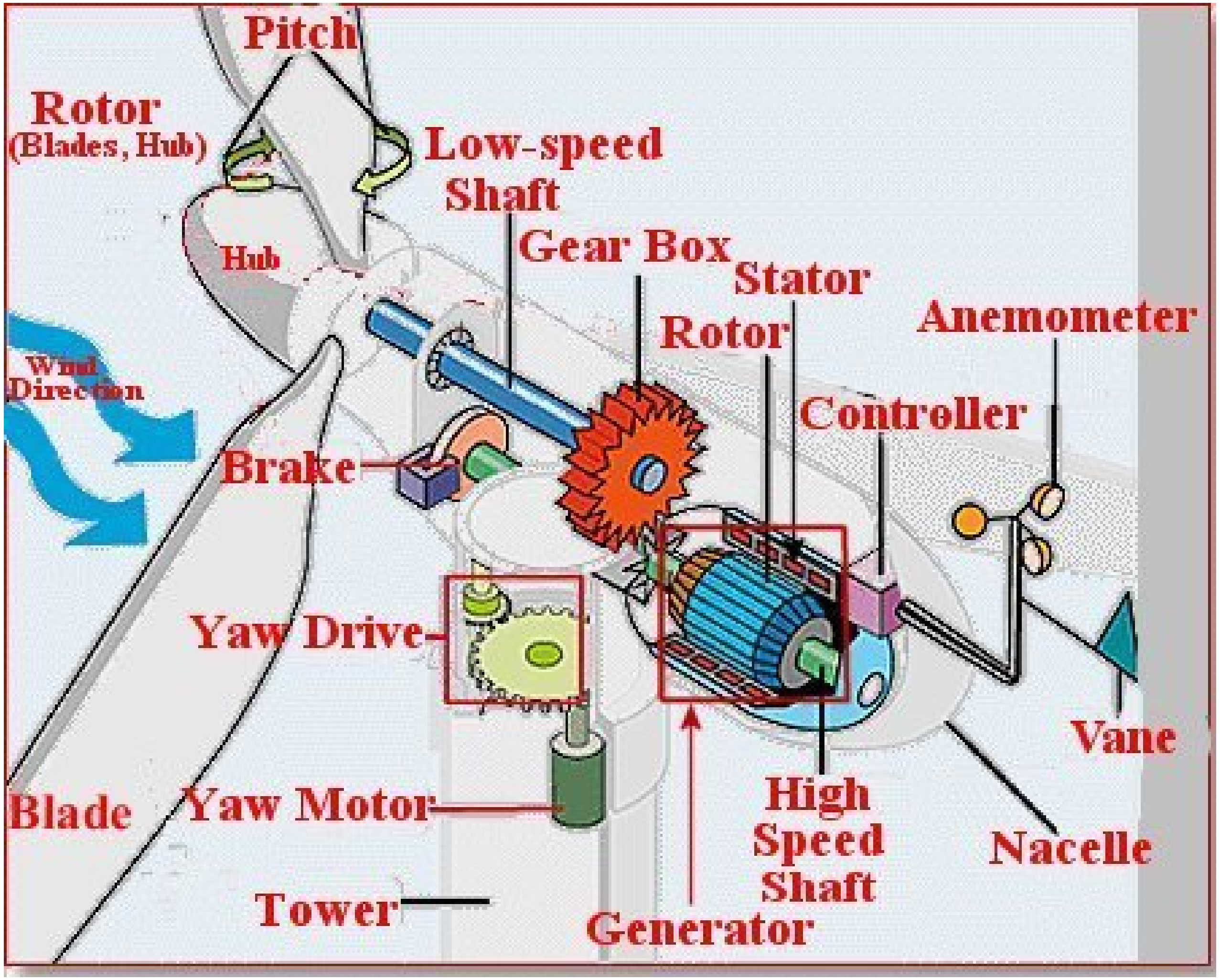
Lake Benton, MN, Wind Farm

POWER CURVE

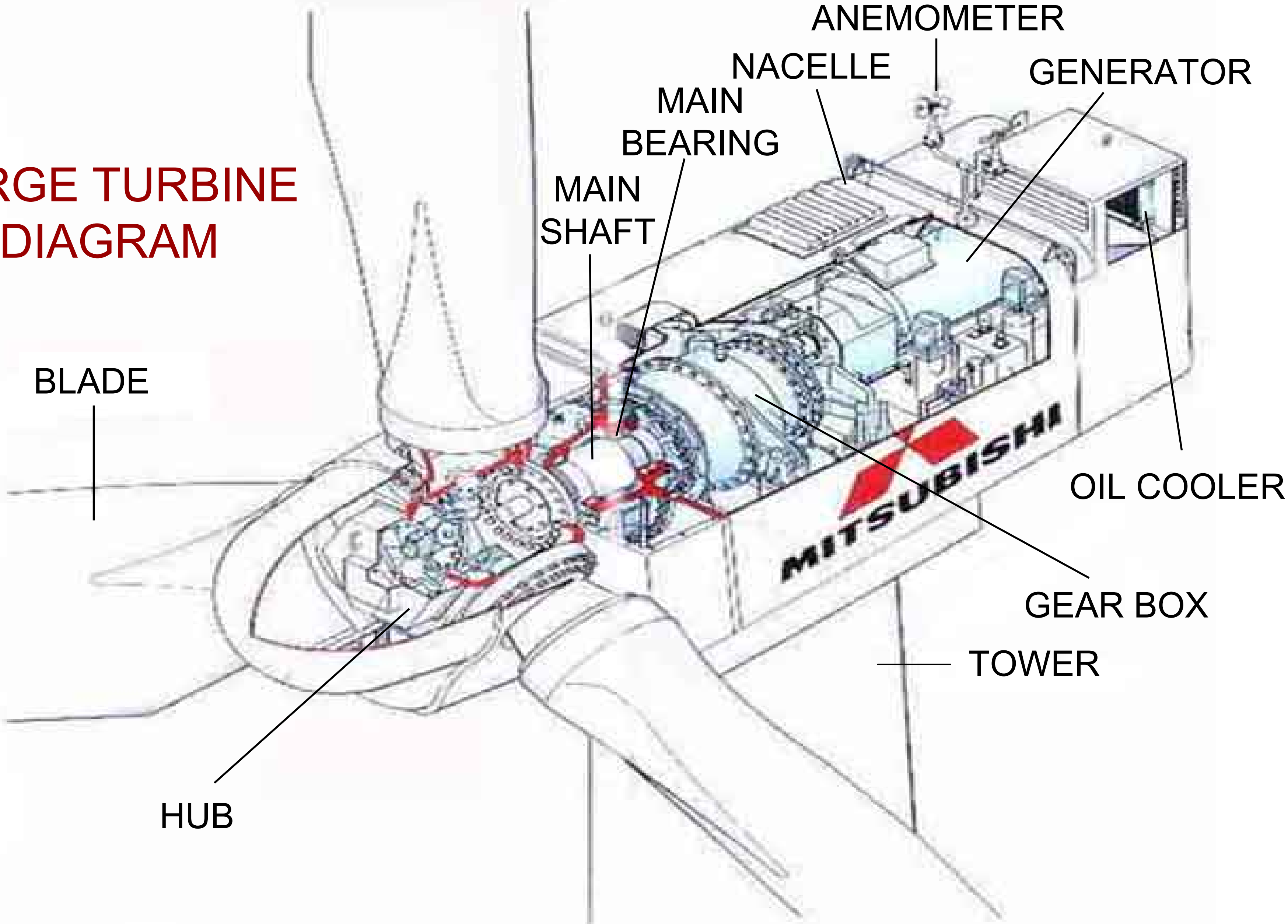



500 kW
1257 m 2
1000 kW
2400 m 2
300 kW
415 m 2
25 kW 78 m 2
10 kW 38 m 2
1 kW 6 m 2

TURBINE DIAGRAM



LARGE TURBINE DIAGRAM



NACELLE 1 MW

BLADE 27 m length

ROTOR AREA = 2460 m^2

ESTIMATION OF ANNUAL ENERGY PRODUCTION

1. GENERATOR SIZE
2. ROTOR AREA and WIND MAP
3. ENERGY vs AVERAGE WIND SPEED
4. CALCULATED: HISTOGRAM & POWER CURVE

GENERATOR SIZE

AKWH = CF * GS * 8760

AKWH	Annual energy production, kWh/yr
CF	Capacity factor (efficiency factor)
GS	Generator Size (rated power), kW
8760	# of hours in a year

GENERATOR SIZE EXAMPLE

AKWH = CF * GS * 8760

CF	35% = 0.35
GS	1 MW = 1000 kW
8760	# of hours in a year

AKWH = 0.35 * 1000 * 8760

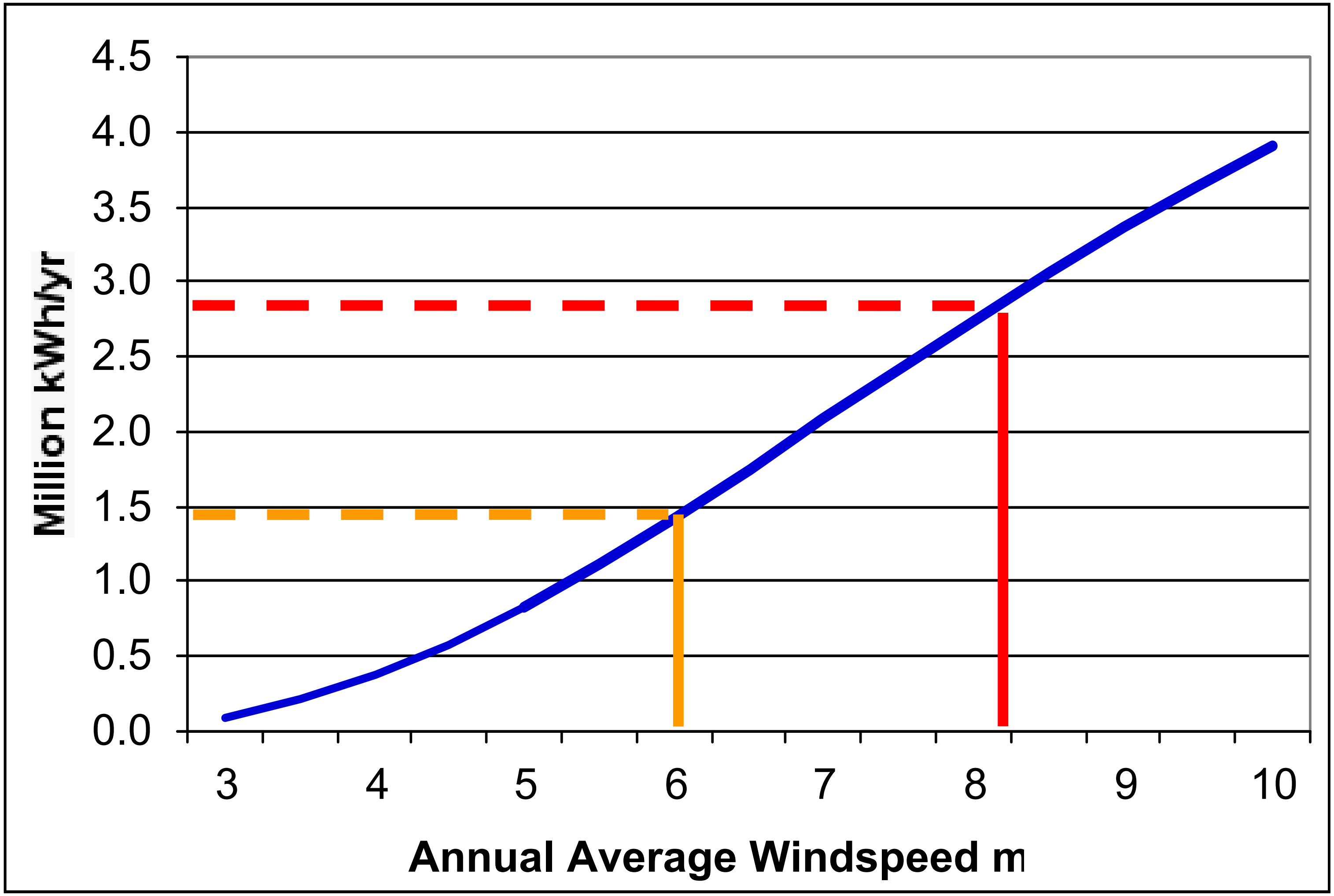
AKWH = 3,060,000 kWh

ROTOR AREA + WIND MAP

$$AKWH = CF * Ar * WM * 8.76$$

AKWH	Annual energy production, kWh/yr
CF	Capacity factor (efficiency factor)
Ar	Rotor Area, m^2
WM	Wind Map Power, W/m^2
8.76	1000 hours in a year
	converts W to kW

ANNUAL ENERGY vs AVERAGE WINDSPEED



CALCULATED ENERGY PRODUCTION

m/s	kW	hr	kWh
1-3	0	1091	0
4	0	760	171
5	34	868	29,538
6	103	914	94,060
7	193	904	174,281
8	308	847	260,760
9	446	756	337,167
10	595	647	384,658
11	748	531	396,855
12	874	419	366,502
13	976	319	311,379
14	1000	234	233,943
15	1000	166	165,690
16	1000	113	113,369
17	1000	75	74,983
18	1000	48	47,964
19	1000	30	29,684
≥ 20	1000	40	39,540
		8760	3,060,545

Rayleigh, 8.2 m/s at 50 m, STD

LEVELIZED COST OF ENERGY

$$COE = \frac{(FCR * ICC) + LRC}{AEP} + AOM$$

COE = LEVELIZED COST OF ENERGY, $/kWh

FCR = FIXED CHARGE RATE, per year

LRC = LEVELIZED REPLACEMENT COST, $/yr (major repairs)

ICC = INITIAL CAPITAL COST, $

AEP = ANNUAL ENERGY PRODUCTION, kWh

A0M = ANNUAL OPERATION & MAINTENANCE, $/kWh

CONSIDERATIONS

Hardware Cost		$670/kW
turbine	$550/kW	
tower	$120/kW	
Installation Cost		$100/kW
foundation, erection, interconnection		
Shipping		$70/kW
Other		$100/kW
ROUND NUMBER		**$1000/kW**

COE EXAMPLE

1 MW TURBINE

FCR = 10% = 0.10

ICC = \$1000/kW = \$1,000,000

LRC = \$5,500

		availability	elevation
AOM =	\$0.01/kWh		
AEP =	2,600,000	98%	1000 m

$$COE = \frac{(0.1 * 1,000,000) + 10,000}{2,700,000} + 0.01$$

COE = \$0.051 / kWh

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